

Final Technical Report

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Magnetic Fluid Friction and Wear Behavior

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Abstract

The friction and wear properties of two groups of magnetic fluids, one developed at NASA Lewis Research Center and a commercial fluid, were evaluated for boundary lubrication. Friction and wear measurements were made using a pin-on-disk apparatus. Three different ball materials were evaluated, (1) 440C, (2) Al₂O₃, and (3) Si₃N₄ against 440C disks. The first class of magnetic fluids have a low vapor pressure hydrocarbon base oil and are suitable for space application. Four variations of this fluid were evaluated: (1) the base oil, (2) base oil with anti-wear additives, (3) a 100 Gauss strength magnetic fluid, and (4) a 400 gauss magnetic fluid. The commercial fluid base oil and four different magnetic particle concentration levels have been evaluated. A space qualified fluorinated lubricant was tested for base line comparison. Hardness, optical microscopy, surface profilometry, and surface analysis were used to characterize the test specimens. Friction was unaffected by the concentration of magnetic particles. Wear rates for magnetic fluids were slightly higher than the base oil. The low vapor pressure magnetic fluid has better wear characteristics than the space qualified fluorinated lubricant.

Introduction

Motivation

The authors proposed the use of magnetic fluids as lubricants in rolling element bearings. The motivating factor is the ability to use a concentrated magnetic field to retain the lubricant in the tribological contact area. The specific application considered involves slow speed scanner bearings for spacecraft. The proposed system would use a full complement hybrid bearing with permanent magnets surrounding the bearing to retain the magnetic fluid lubricant in the raceway track. Other investigators have proposed using magnetic fluids as lubricants for gear contacts and journal bearings. This research addressed the boundary lubrication performance of five grades of a common commercial magnetic fluid and three grades of a specialized low vapor pressure magnetic fluid.

Materials

Ball Properties

All friction and wear tests were run using 9.5 mm diameter balls. Three ball materials, including one bearing steel and two ceramics, were used. The steel balls were composed of 440C hardened to 58 RC and were Grade ABEC 10. Grade 25 aluminum oxide and

Grade 5 silicon nitride balls were the ceramics used. The maximum geometrical variance of these balls is shown in Table 1.

Material	Grade	Diameter Variation	Spherical Deviation	Surface Roughness
440C	10	.25 μm	.25 μm	.025 μm
Al ₂ O ₃	25	.60 μm	.60 μm	.05 μm
Si ₃ N ₄	5	.13 μm	.13 μm	.02 μm
Table 1- Geometrical variance of the balls				

Disk Properties

The wear disks used had a diameter of 64 mm and thickness of 13 mm. The disk composition was 440C HT (high temperature) stainless steel. This is modified 440C stainless containing 3.75-4.25% molybdenum, five times the typical concentration. Surface roughness varied between .35-.45 μm RMS. All disks had a hardness of 56.5 to 58.5 on the Rockwell C scale.

A five-step process was used to achieve the required surface finish. Initially the disks were ground flat with a surface grinder with a magnetic mount. The magnetically charged disks were then degaussed. This was followed by a four-step wet sanding using 160, 240, 400, and 600 grit paper. After sanding, the disk was polished with 9 and 6 micron diamond paste. Finally, the disks were lapped using 3 micron alumina paste on a polishing wheel.

Lubricant Properties

Three different base oils were used, a low vapor pressure synthetic hydrocarbon (fluid N), a hydrocarbon (Fluid A), and a perfluoropolyether fluid (Fluid K). Magnetic fluids based on Fluid N and Fluid A were tested. Fluid K is a standard space qualified lubricant that was tested for comparative purposes.

Four different formulations of Fluid N were tested. The base oil NYE200A and a formulation with antiwear additives was obtained directly from the manufacturer. Two magnetic fluids were formulated using the base oil. The fluids, designated NASA-100G and NASA-400G, have saturation magnetization levels of 100 and 400 gauss, respectively. There is a significant increase in viscosity and magnetic particle concentration between the 100G and 400G fluids.

The second group of lubricants based on Fluid A are commercially available magnetic fluids. This group of fluids were studied to distinguish the effect of magnetic particle concentration on friction and wear. Four different magnetic saturation strength fluids were tested from 100 to 400 gauss strength. The base oil was also tested.

Fluid K is a space qualified lubricant which was tested as a baseline. A single viscosity grade of the fluid was tested. This fluid is synthesized using CsF catalyzed polymerization of hexafluoropropene oxide (HFPO) yielding a branched polymer structure.

Low Vapor Pressure Magnetic Fluids				
	NYE2001A	NYE2001	NASA-100G	NASA-400G
Base fluid	Syn. Hydro	Syn. Hydro	Syn. Hydro	Syn. Hydro
Anti-Wear Add	No	Yes	No	No
Magnetic Add	No	No	Yes	Yes
Saturation Mag.	0	0	100	400
Vapor Pressure, Torr			2.4e-9	9.9e-10
Evap. At 175C, gm/cm2-sec			3e-8	3e-8
Particle Size, A	None	None	100	100
Viscosity@27C,cp			320	4400
Pour Point			-55	-17
Density@25C,gm/ml			.95	1.28
Thermal Cond @38C, mW/mK			125	191
Electrical Res ohm-cm			>10e9	>10e9
Table 2				

Commercial Magnetic Fluids					
	APG Base	APG311	APG312	APG313	APG314
Base fluid					
Anti-Wear Add	No	Yes	Yes	Yes	Yes
Magnetic Add	No	100	150	200	250
Saturation Mag.	0				
Vapor Pressure, Torr		4.0e-7	4.0e-7	4.0e-7	4.0e-7
Evap. At 175C, gm/cm2-sec					
Particle Size, A	None				
Viscosity@27C,cp		70	90	125	150
Pour Point		-62	-60	-58	-55
Density@25C,gm/ml		0.94	1.00	1.06	1.09
Thermal Cond @38C, mW/mK		125	130	134	140
Electrical Res ohm-cm					
Table 3					

Test Method

Ball-on-Disk Tester

All friction and wear measurements in this study were conducted using a ball-on-disk tribometer. The wear couple consists of a ball and a plate. A 9.5 mm ball and a 64 mm disk were used.

Three wear tests were run on each disk by adjusting the radial ball position relative to the disk. A plastic ring projecting 2mm over the surface of the disk was used to retain the lubricant. Friction coefficient, wear volume, and surface analysis measurements are made during the test. Friction coefficient was measured using a strain gage transducer. Optical measurements of the wear diameter were made after 1, 3, 7, 15, 30, and 50 kilocycles of sliding. This corresponds to 135, 400, 950, 2050, 4100, and 7200 meters of sliding. The ball holder was removed from the test rig at each interval. A microscope with a digital camera was used to make an optical micrograph of the ball wear scar. The wear scar diameter was measured directly with an objective scale and confirmed with measurements from the micrographs. The ball holder was reinstalled in the test rig in the original orientation using a witness mark. Scanning electron micrographs of selected ball wear scars were made after 50 kilocycles (7200 m). The rig was located in a plastic environmental chamber with a filtered purge air-line. The atmosphere was maintained at less than 1% RH. Tests were conducted at room temperature. A 1 ml lubricant charge was used in each test. This resulted in a flooded contact. The wear track diameter was 41-46 mm. The majority of the tests were conducted at 200 RPM with a sliding speed of 0.42 m/s to 0.48 m/s. Tests on the highest viscosity fluid were run at 0.046 m/s (20 RPM) and 0.12 m/s (50 RPM) sliding speed. A 2 kg deadweight normal load was applied on all tests. The maximum initial Hertzian contact stress was 1.264 GPa using the 440C steel ball and 1.427 GPa using a silicon nitride ball. The mean and maximum Hertz contact stresses for each wear couple are shown in Table 4.

Wear Couple Material Ball / Disk	Mean Initial Hertz Stress	Max Initial Hertz Stress
440C / 440C	.843 GPa	1.264 GPa
Al ₂ O ₃ / 440C	.946 GPa	1.418 GPa
Si ₃ N ₄ / 440C	.951 GPa	1.427 GPa
Table 4- Initial Hertz Stresses		

Test Procedure

Sample Preparation

A three-step solvent based cleaning procedure was used for the balls and the disks. Specimens were cleaned using hexane, acetone, and methanol. At each stage the samples

were placed in a beaker, immersed in the solvent, and placed in an ultrasonic bath for 10 minutes at room temperature.

Wear test

The ball-on-disk apparatus was used for all the friction and wear testing. The total duration of each test was 50 kilocycles. Each test was stopped at 1, 3, 7, 15, 30, and 50 kilocycles in order to make intermediate wear measurements. The ball holder was removed and the wear scar was measured using an optical microscope. Optical micrographs were taken if there was anomalous wear behavior. The maximum, minimum, and average friction coefficient was recorded for each interval. At the end of the test, wear scar measurements and optical micrographs were taken of the ball wear scar. Disk wear track measurements were made with a stylus profilometer. Selected specimens were analyzed using scanning electron microscopy (SEM).

Results

Friction and Wear

Results are presented in the following in graphical or tabular form for the identified fluids.

NYE based fluids

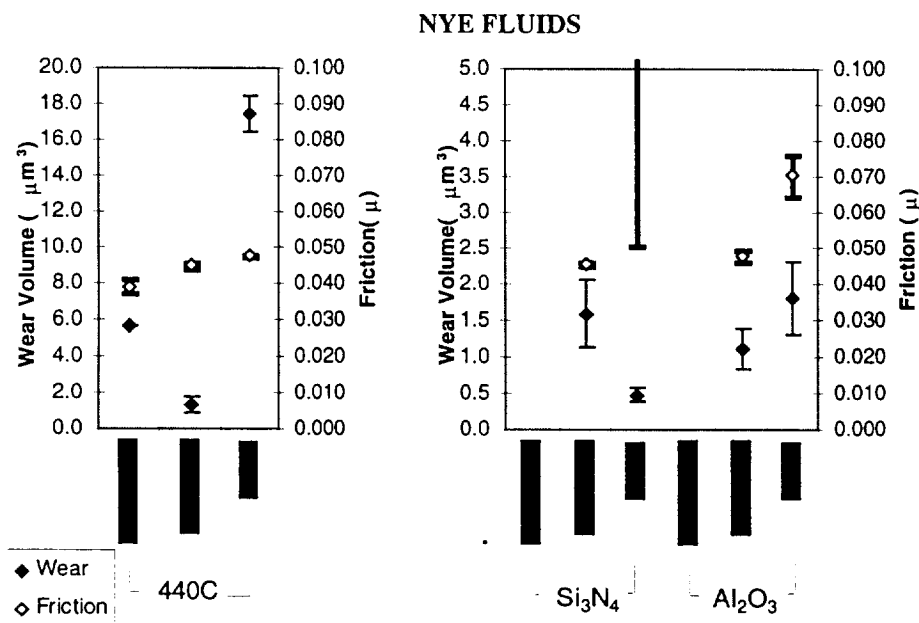


Figure 1

APG based fluids

APG FLUIDS

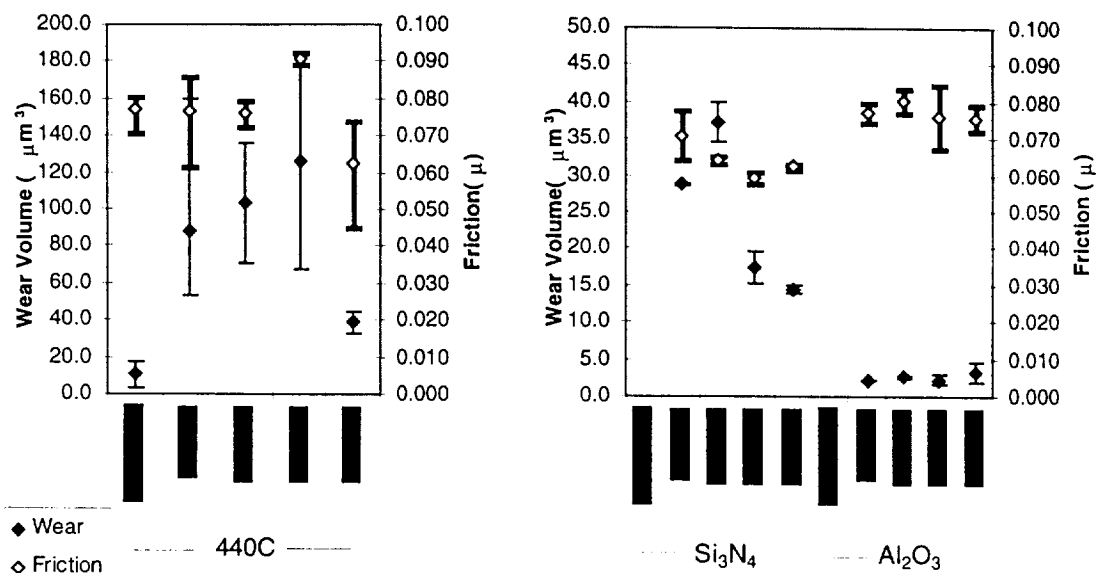


Figure 2

NYE 400 and Krytox

Disk	Ball	Lub	#Test	Wear Rate μm				Friction Coefficient μ			
				Mean	Max	Min	Std	Mean	Max	Min	Std
440C	440C	NYE_base	2	5.6	5.6	5.6	.006	.039	.041	.037	.00259
	440C	NYE_add	2	1.3	1.8	0.9	0.61	.045	.046	.044	.00106
	440C	N100G	2	17.4	18.4	16.5	1.4	.048	.048	.048	.00011
	Si ₃ N ₄	NYE_base									
	Si ₃ N ₄	NYE_add	2	1.6	2.1	1.1	0.65	.046	.046	.046	.00083
	Si ₃ N ₄	N100G	2	0.5	0.6	.4	0.14	.105	.160	.050	.07755
	Al ₂ O ₃	NYE_base									
	Al ₂ O ₃	NYE_add	2	1.1	1.4	.8	0.38	.048	.050	.046	.00236
	Al ₂ O ₃	N100G	2	1.8	2.3	1.3	0.71	.070	.076	.065	.00825
	440C	Krytox 143AC	3	63.7	1.33	21.8	60.5				
440C	440C	APG_base	3	10.7	17.3	3.5	6.9	.077	.081	.070	.00593
	440C	APG_311	3	88.5	159.0	52.9	61.4	.077	.086	.061	.01337
	440C	APG_312	2	103.0	136.0	71.2	45.5	.076	.079	.073	.00471
	440C	APG_313	2	126.0	185.0	67.5	83.0	.091	.093	.089	.00230
	440C	APG_314	3	38.9	44.4	32.9	5.75	.063	.074	.045	.01553
	Si ₃ N ₄	APG_base									
	Si ₃ N ₄	APG 311	2	28.8	28.9	28.6	0.17	.071	.078	.064	.00943
	Si ₃ N ₄	APG 312	2	37.2	39.9	34.4	3.9	.064	.065	.063	.00153
	Si ₃ N ₄	APG 313	2	17.4	19.5	15.2	3.0	.059	.061	.058	.00224
	Si ₃ N ₄	APG 314	2	14.4	15.0	13.9	0.77	.062	.063	.062	.00106
	Al ₂ O ₃	APG_base									
	Al ₂ O ₃	APG 311	2	2.2	2.3	2.1	.087	.077	.080	.075	.00389
	Al ₂ O ₃	APG 312	2	2.7	2.8	2.5	0.25	.080	.084	.077	.00469
	Al ₂ O ₃	APG 313	2	2.3	2.9	1.7	0.85	.076	.085	.067	.01261
	Al ₂ O ₃	APG 314	2	3.2	4.7	1.8	0.21	.076	.079	.072	.00495

Table 5 Tribological Results

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December 11, 1998

Deborah King
Grants Officer
NASA Lewis Research Center
21000 Brookpark Rd.
Cleveland, Ohio 44135

Dear Ms. King:

I am writing you in order to completely close-out a funded project that I have had with the NASA Lewis Research Center. To comply with grant procedures, I am sending along with this letter a copy of the final report. Copies have also been sent to CASI, to the NASA Technical Monitor and to the University of Toledo Grant Offices. The NASA grant number for the project was NCC3-558.

Hopefully, I have provided all necessary information for you to close the file on this project. If I have not, please contact me either at the University of Toledo (419) 530-8232 or at the Ohio Aerospace Institute (440) 962-3030.

Sincerely,

Theo G. Keith

Theo G. Keith, Jr.
Distinguished University Professor

cc: UT Office of Research, UT Grants Accounting